

Space Shuttle Main Engine Debris Testing Methodology and Impact Tolerances

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In the wake of the Space Shuttle Columbia disaster every effort is being made to determine the susceptibility of Space Shuttle elements to debris impacts. Ice and frost debris is formed around the aft heat shield closure of the orbiter and liquid hydrogen feedlines. This debris has been observed to liberate upon lift-off of the shuttle and presents potentially dangerous conditions to the Space Shuttle Main Engine. This paper describes the testing done to determine the impact tolerance of the Space Shuttle Main Engine nozzle coolant tubes to ice strikes originating from the launch pad or other parts of the shuttle.

Nomenclature

<i>F</i>	=	Degrees Fahrenheit
<i>g_c</i>	=	Gravitational constant, 32.2 ft/sec ²
<i>KE</i>	=	Normal Kinetic Energy in foot-pounds, lbf-ft
<i>KSC</i>	=	Kennedy Space Center
<i>LH2</i>	=	Cryogenic Liquid Hydrogen
<i>LOX</i>	=	Cryogenic Liquid Oxygen
<i>m</i>	=	Mass in pounds, lb.
<i>MECO</i>	=	Main Engine Cut-off
<i>MSFC</i>	=	Marshall Space Flight Center
<i>n</i>	=	Angle of nozzle test article in degrees, °
<i>OMS</i>	=	Orbital Maneuvering System
<i>P_{cf}</i>	=	Density, in pounds per cubic foot
<i>psi</i>	=	pounds per square inch
<i>SSME</i>	=	Space Shuttle Main Engine
<i>v</i>	=	Velocity, in feet per second
<i>x</i>	=	Height, in feet

I. Introduction

The Space Shuttle Main Engine is a reusable liquid rocket engine propelled with liquid hydrogen and liquid oxygen. The 3 engines on the aft end of the Space Shuttle orbiter operate for 8.5 minutes during ascent to orbit of the Space Transportation System (STS). The converging-diverging regeneratively fuel-cooled nozzle on the SSME expands and increases the velocity of the combustion exhaust gases. The nozzle is approximately 113 inches in length and has a 94-inch exit diameter¹.

The nozzle is manufactured from 1,080 individual A286 Stainless Steel coolant tubes. These tubes are thin-walled and roughly 1/4" in diameter brazed together and to the structural jacket². The nickel-alloy structural jacket has a series of nine structural hatbands for hoop strength. The fuel is supplied to the nozzle from the high-pressure fuel turbopump at 6,000 psi. It enters the nozzle from the diffuser and is then routed through the downcomer lines into the aft manifold³. The fuel is routed upwards in a single pass through the nozzle tubes to cool the inner wall of the nozzle increasing in temperature by 400° F in about two milliseconds¹. The hydrogen collects in the forward manifold then onto the mixer bowl to combine with the bypass flow from the coolant control valve. The nozzle configuration can be found in Figure 1⁴.

Liquid Hydrogen at -423 °F is used during chill-down and is the propellant for the Space Shuttle Main Engines (SSME) on the Shuttle Orbiter. As a result of the cold temperatures and generally warm humid air on the launch

pad, ice and frost (hereafter referred to as ice) form around the heat shield retainer ring and LH2 feedlines. During lift-off, vibration and heat separates the ice from the retainer and LH2 feedlines and it has been observed to impact the nozzle, both jacket and bare tubes. Another debris source that presents potentially dangerous conditions to the nozzle is rust scale from the Kennedy Space Center (KSC) launch pad.

If the impact causes a leak in the cooling tubes the engine control system makes up for the loss of fuel flow to the main combustion chamber by increasing the LOX flow rate. There are four possible outcomes depending on the leak rate. 1) A small fuel leak rate is acceptable and would not affect the mission. 2) A greater fuel leak rate would cause an early main engine cutoff (MECO) due to low LOX level. Using the OMS engines could make up the low cutoff velocity⁵. 3) If the fuel leak rate were too large for the OMS engines to make up, the mission could be lost. 4) If leakage is large enough, the preburner mixture ratio and therefore temperature would increase causing a redline to be triggered by the preburner and the mission could be lost.

In order to fully understand the effects of ice and rust debris impacts to the SSME nozzle, testing was conducted at the Marshall Space Flight Center (MSFC). Traditional impact methods with air projectile guns were not applicable to the low velocity impact cases as required. Instead, the drop tube within the Dynamic Test Facility at MSFC was utilized to obtain velocities up to 120 feet per second. Similar operating conditions of the nozzle were replicated including hardware configurations, manufacturing techniques, and pressures. The primary objective of testing was to determine the tolerances of the nozzle to ice and rust debris and obtain data for dynamic and impact modeling correlations.

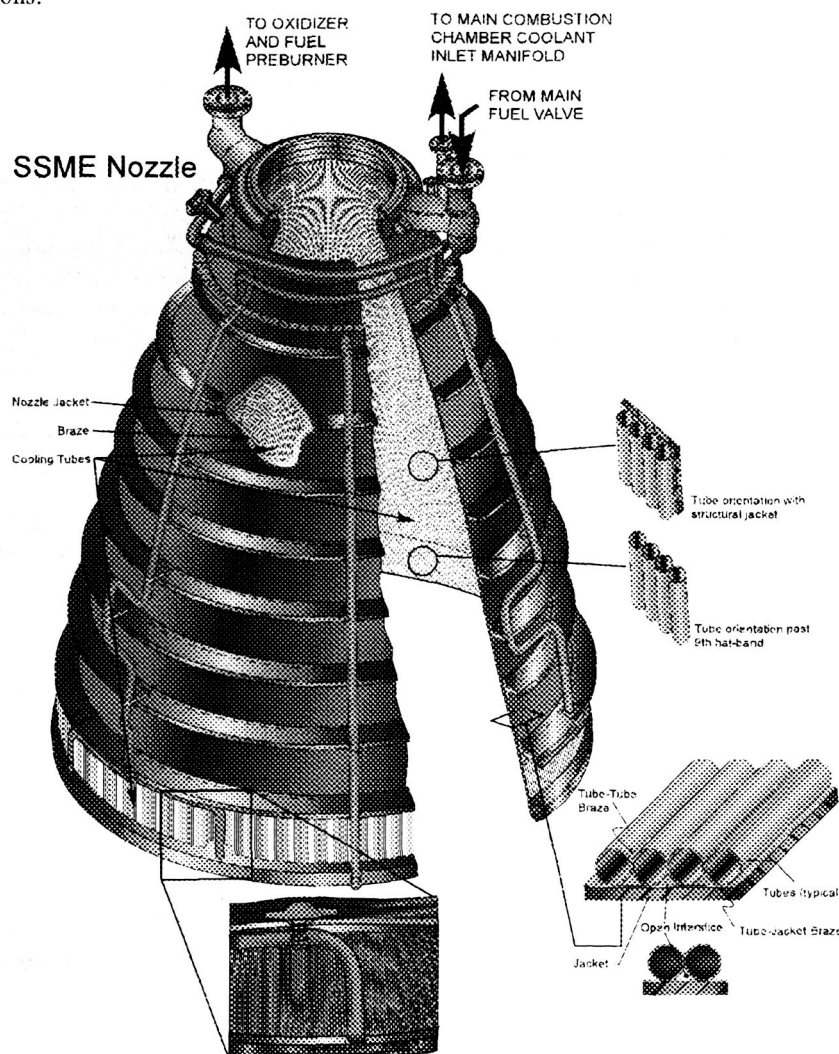


Figure 1. Space Shuttle Main Engine Nozzle Configuration.

II. Testing Overview and Configuration

A. Dynamic Test Facility Drop Tube

SSME impact testing was performed at the Dynamic Test Facility Drop Tower at MSFC. The drop tower comprises a 10-inch diameter, 345-foot drop tube that has various ports for drops at multiple heights within the tube. The tube was configured with two high-tension cables located in the center of the tube, held in place with fabricated plates for both the top and the bottom. The cables were tensioned with threaded rods attached to the plates and drop tube flanges (both the top and bottom plate). A sized hole was machined in the bottom plate in which the sabot would be stripped and the projectile would continue through onto the test article.

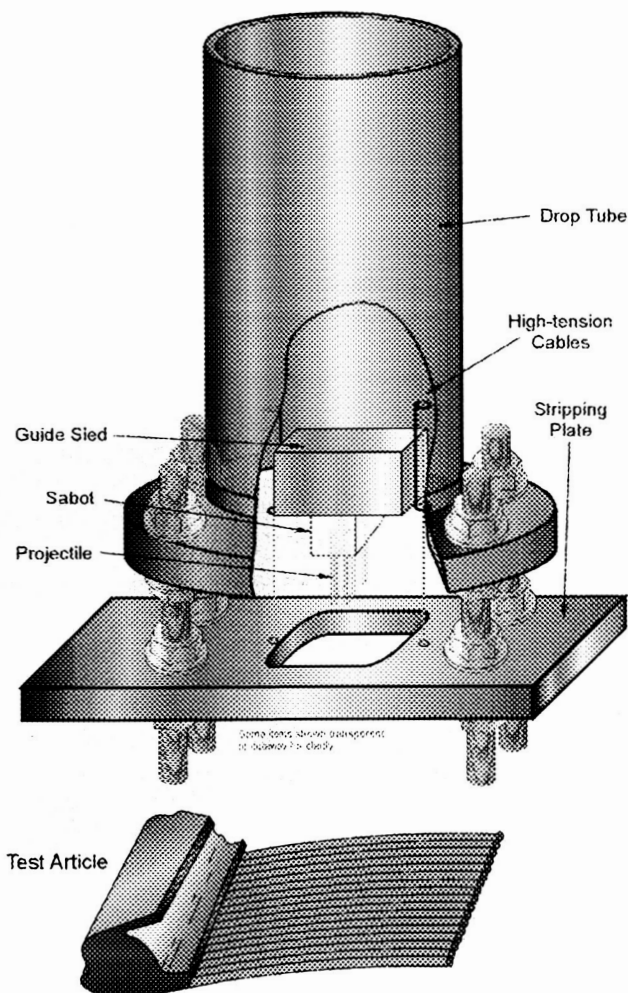


Figure 2. Drop Tube Configuration.

A sled system was designed to fit the width of the cables and was used to guide the projectiles down the cable. As part of the sled system, foam sabots were attached to the underside of the sled to hold the projectile in place. The sabot had a countersunk hole machined in center that was sized for the 1.5" x 0.75" cross section ice projectiles. The sabots were designed in such a way to fracture symmetrically and release the projectile normal to the test article. The same sabot configuration was used to hold the rust samples and Inconel wedges in place.

In order to determine at which heights the sled system would need to be dropped to achieve the required velocity, a series of Calibration Drops were performed using a surrogate specimen. The surrogate specimen was manufactured from MCC-1 cork and had an identical cross section of the ice samples, as well as a density similar to low-density ice. Following a series of drops, the height of each drop was plotted against the velocity calculated and a function was developed to fit this data. This data is compared with the calculated value for a similar specimen in

Figure 3. The error in the graph is due to slight configuration differences between the actual test set-up and the calculated model. The primary factors were the cross-sectional area of sled system, and the friction between the sled and the tensioned cables.

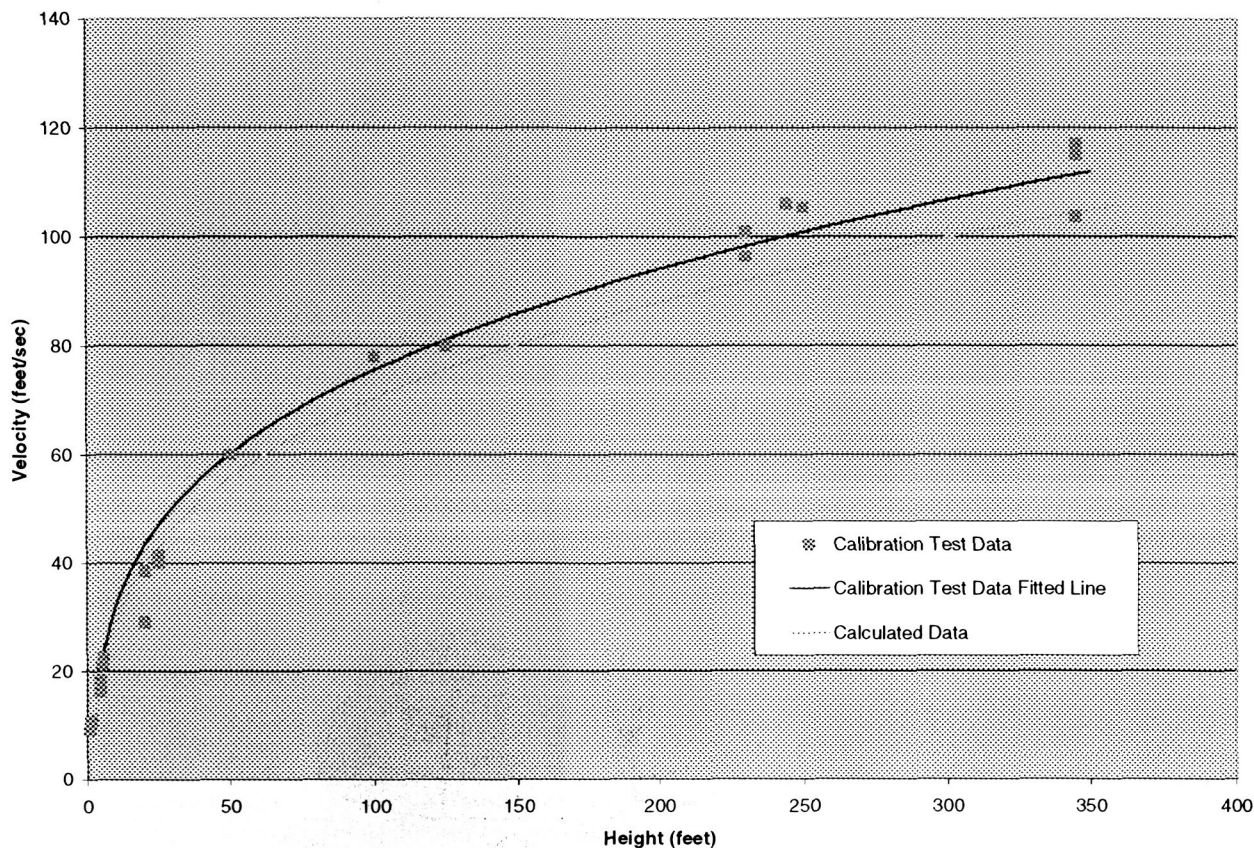


Figure 3. Determination of Required Drop Height for Expected Velocity.

The function developed according with the sled configuration can be found in Equation 1. This equation was used as a rough estimate to determine an approximate drop height to obtain the expected impact velocity on the test panel for each drop.

$$v = \frac{(18.7 \times \ln x - 4.6) + (9.6 \times x^{0.43})}{2} \quad (1)$$

where:

v = Estimated Impact Velocity in feet per second, fps

x = drop height in feet, ft

B. Test Article and Holding Fixture Configurations

The test panel was a sectioned panel from depleted flight and development hardware. The two nozzles that were sectioned for purpose of this testing were 2032 and 5009. Two types of panels were used for the testing program: a panel with bare tubes and a panel with the jacket section included. This hardware went through identical manufacturing processes as a flight nozzle. The panel with bare tubes was sectioned from the 10th bay of the nozzle and the tubes were cut off directly below the 9th hatband. A closeout manifold for the forward end of the panel was fabricated and brazed to the tubes. The aft manifold was closed out with machined bosses welded into the main manifold and the closeout ring. The manifold boss was tapped to accommodate AN fittings in order to pressurize the panel to 6,000 psi with water. The large panel was section from the aft end of the nozzle and cut just above the 8th

hatband. A similar manifold was fabricated to closeout the tubes and bosses for the aft manifold. A total of 22 panels were tested, including 20 small panels and 2 large panels.

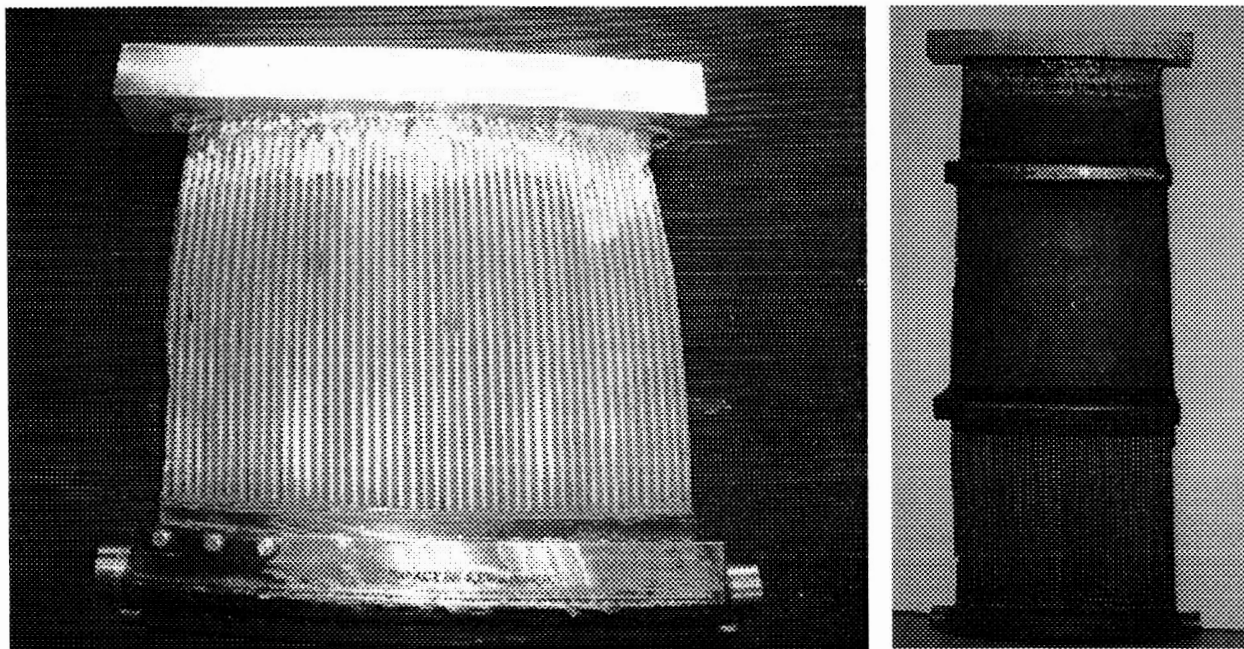


Figure 4. Small and Large Test Panel Configurations.

The fixture to restrain the panels was fabricated to accommodate various impact angles. The panel was held in the fixture by four primary attach points. Two bolts were threaded into the tube closeout manifold and two brackets were tightened to hold the aft manifold in place. A torque of 42 lbf-ft was applied to the brackets on each panel installation for model correlation purposes. The fixture was also designed to accommodate both the large and small test panels. The large panels used an additional structural support through the ninth hatband. In most test cases, the panel was kept in fixture for subsequent tests to allow for repeatability. There were two configurations of the fixture and test-article set-up. The first set-up was configured with the fixture and panel normal (90-degrees) to the debris direction of travel, while other test configuration was 45-degrees relative to the direction of projectile travel. The panel and fixture configuration can be found in **Error! Reference source not found..**

C. Instrumentation

The test article included instrumentation to measure strain, temperature, and dynamic data. A total of three thermocouples (two on the test article, one near the drop tube), two accelerometers, and four strain gauges were included on the test article. All strain gauges and thermocouples were installed on the hot-wall side of the test article. Some cases where access was limited, the accelerometers were installed on the cold-wall side of the nozzle not to interfere with the impact area. All instrumentation was sampled at 200,000 samples per second. The instrumentation configuration installed on a test article can be found in **Error! Reference source not found..**

In addition to the data acquisition system, high speed video cameras were used to capture velocity data and analyze the mechanics of each drop. The three cameras were positioned to: view the entire panel, a close up of the impact zone, and a camera above the impact zone to calculate the projectile velocity.

D. Debris and Test Projectiles

Three primary sources of debris were tested in the nozzle impact testing. This included high density ice, low density ice and rust scale. Additional testing was completed with machined Inconel wedges as damage limit testing for rust. This is an unexpected debris and used only for demonstration purposes. The density required in the test plan for low density ice was 37 ± 4 pcf. The high density ice was specified to be 57.5 ± 3 pcf. All ice projectiles were weighed and handled using special gloves to prevent any degradation or melting. The time in which the ice projectiles were exposed to atmospheric conditions outside of the freezer unit was minimized to five minutes or less.

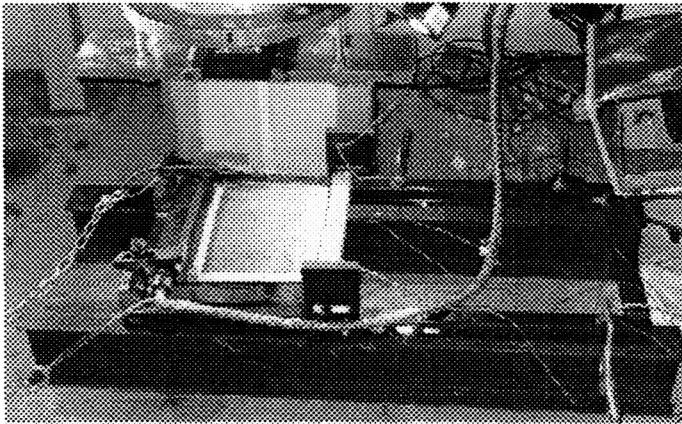


Figure 6. Small Panel in Holding Fixture.

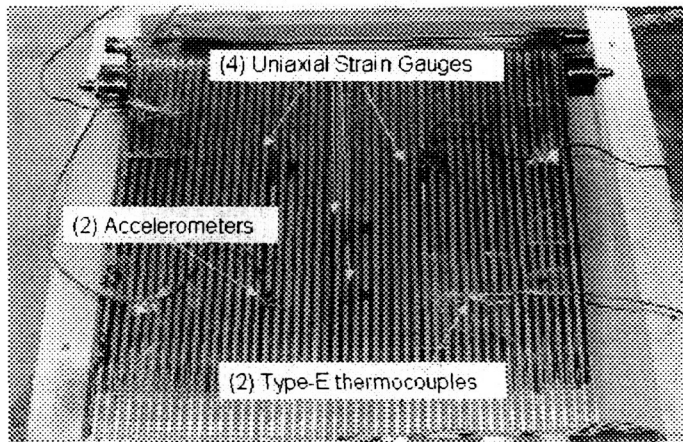


Figure 6. Instrumentation Configuration for Test Articles.

The drop tower at the Dynamic Test Facility (Building 4550 at MSFC) was prepared for drop testing starting in October 2004. This included removing existing instrumentation and tube port protrusions that would disturb the descent path of the projectiles. The lower level facility in which the nozzle panel and instrumentation would be present within was set-up to accommodate the test articles.

Two high-tensioned guide cables were secured within the drop tube using a fabricated plate for both the top and bottom of the tube flanges. A guide sled and sabot system was designed and fabricated to hold the projectiles central to the tube. A series of test drops were conducted to validate various sled and sabot configurations. After the sled and sabot design was finalized, an additional series of testing was conducted to determine the heights required to obtain various target velocities with the configuration. This was done using an identical density surrogate specimen as the low density ice projectiles.

Following approval of safety and quality inspections of the test procedures and facilities, and a test readiness review, a series of calibration drops were performed using low density and high density ice projectiles. These drops were identical to the actual drops in the full test matrix and for all intensive purposes, could be used as actual drop data. The panels were fully pressurized and all instrumentation and video data was recorded.

A typical drop test would be initiated by the installation of the nozzle panel into the test fixture. All instrumentation, including thermocouples, accelerometers, and strain gauges were connected to the data acquisition

Rust scale was selected from liberated debris sent up to MSFC from the KSC launch pad. The sizes selected for testing were above the current requirement for allowable sizes on the pad. The allowable sizes for rust on the pad are roughly that of a quarter.

Inconel wedges were used for damage limit testing to impart the maximum kinetic energy into the nozzle coolant tubes. Three types of Inconel wedges were used in order to obtain the various required energies. Dimensions of all three wedges were the same however; holes were drilled into each wedge to vary the weights of each. The impacting edge of the wedge had a width of 0.020" for each of the wedges. The corners of the impacting wedges were rounded.

III. General Testing Procedures

The SSME Nozzle Impact test program was initiated in August 2004. A test plan was written by ER32/Combustion Devices and approved by Level III (Space Shuttle Main Engine Project Office) and Level II (Space Shuttle Program

system. The pressure lines were connected to the pressure system and a leak check of the lines and nozzle panel was conducted. While these activities were taking place, the drop technicians would set-up any sled/sabot equipment needed for that particular drop. The technicians would also start to measure and weigh the projectile. If ice was being used, the projectile would remain in the freezer until the test was ready to be conducted. Pre-test photographs and observations would be recorded of the nozzle panel condition. After all personnel were clear, the drop room was closed to prevent anyone from entering during the test.

The technicians would take the projectile to the port required of the particular drop test and install in the sabot in preparation for the drop. Pressurization to the nozzle panel would begin. At the same time, the video and instrumentation engineers would start recording the data for the drop. The panel would be illuminated with high intensity lighting in preparation for the drop. The test conductor would initiate communication and request a confirmation from all test engineers and technicians to begin the test. The drop was then performed. After confirmation that the projectile had impacted the nozzle panel, the nozzle panel was immediately depressurized and verified that pressures were at safe levels. All recording of video and instrumentation data would be stopped. The drop room would then be cleared for personnel to enter and the high intensity lighting would be turned off.

Personnel would then conduct post-test inspections of the nozzle panel. This included post-test photographs, visual inspection and contour inspections for any damage. All data was recorded on a test data sheet. The video test engineer would calculate the velocity and an evaluation was made to repeat the test or continue with the subsequent tests in the matrix. An identical process was followed for each drop test conducted on small and large impact test panels.

IV. Hardware Inspections and Test Data

Pre-test and Post-test inspections were performed previous to and immediately following each drop test. This included both a visual inspection of the impacted nozzle panel and contour inspection with one's hands. The inspector was looking for any changes in the characteristics of the nozzle tubes, including, but not limited to cracks, buckling, dents, indentations, surface roughness, and ruptures. Pre-test and post-test photographs were taken for each drop test to keep records of each condition.

A total of 58 tests were conducted using ice projectiles; 20 calibration tests, 14 tests with low density ice, and 24 tests with high density ice. None of the tests showed any damage with drops using either low-density or high-density ice projectiles on either the small (bare tubes) or large (jacket section) test nozzle panels up to maximum test velocity of 120 feet per second. In all drops the energy was dissipated by the ice in which the ice would shatter.

A total of 5 drops were completed using rust debris at various masses and velocities. All rust samples were dropped with the sharp edges normal to the nozzle test panel, impacting across the tubes circumferentially. Post-test inspections of rust drops revealed slight surface scratches and rust residue on the nozzle tubes. A majority of the residue and scratches were removed by wiping with a dry cloth or one's fingers. When the inspectors performed the contour inspections, a slight mark scratch could be felt, but also easily missed if rust residue had not been present to identify the area. One drop revealed a minor dent in one nozzle tube, but no ruptures were present.

Damage limit testing was performed with Inconel wedges to understand the energy which would cause a tube to rupture. A total of ten tests were completed with the Inconel wedges. The purpose of testing with the wedges was to determine the kinetic energy required to rupture nozzle coolant tubes. This was classified as damage limit testing. This is an unexpected debris source and only used for demonstration purposes. Nozzle coolant tubes demonstrated impact tolerance with Inconel wedges up to a normal kinetic energy of 75.9 lb-ft (total energy) and a corresponding velocity of 105.6 fps without any tube ruptures. The damage limit testing with Inconel wedges revealed that ruptures occurred above a normal kinetic energy of 83.8 lb-ft (total energy) and corresponding velocity of 110.9 fps. This energy was spread across a total of six nozzle tubes for both cases. This data can be found in Figure 7. The normal kinetic energy was found using Equation 2.

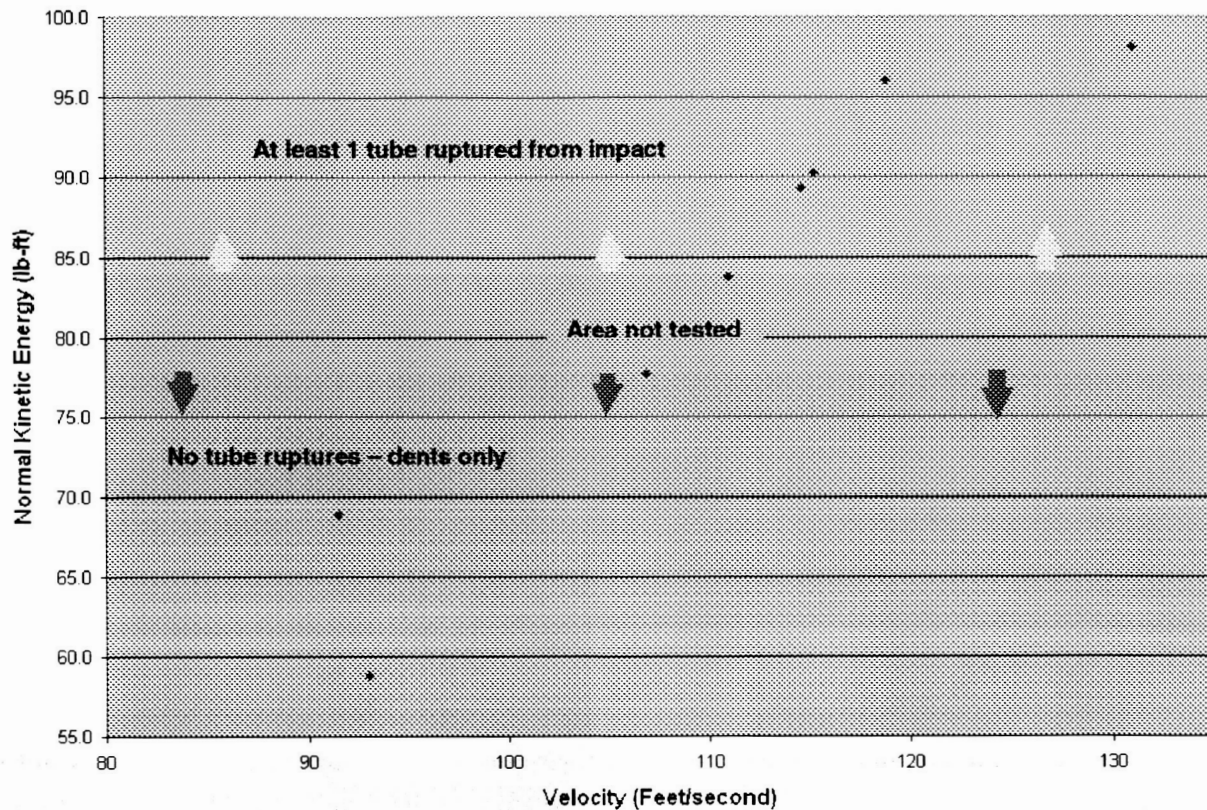


Figure 7. Total Kinetic Energies for Inconel Damage Limit Testing.

$$KE = \frac{mv^2}{2g_c} \times [\cos(90 - n)]^2 \quad (2)$$

where:

KE = Normal Kinetic Energy in foot-pounds, lb-ft

m = mass in pounds, lb.

v = velocity in feet per second, fps

g_c = gravitational constant, ft/sec²

n = angle of nozzle test article in degrees, °

An incident on STS-93 caused the rupture of three nozzle coolant tubes during mainstage of the flight. A LOX post pin ejected from a deactivated LOX post impacted the hot-wall side of the nozzle. This caused a fuel leak and a MECO at 0.16 seconds prior to the planned cut-off at T+ 8 minutes 30 seconds⁶. The result of this was failure scenario 2 as outlined in the Introduction. Aerothermal analysis was completed and the energy that ruptured the tubes was determined. Taking this analysis for the 1.5 gram pin at a velocity of 700 – 900 feet per second, the corresponding energy that caused the three tubes to rupture ranges from 25.2 lbf-ft to 41.6 lbf-ft⁷. Since this energy was spread across three tubes, the energy per tube that caused a rupture ranges from 8.4 lbf-ft to 13.9 lbf-ft.

The test data indicated that it took a normal kinetic energy of at least 14 lbf-ft to rupture a single nozzle coolant tube. This is the lowest energy that ruptured at least one nozzle coolant tube. This data is compared with the original analysis from the STS-93 LOX post pin failure. The test data falls within the range of the calculated LOX post pin failure and provides a reasonable validation.

V. Conclusion

The Space Shuttle Main Engine nozzle coolant tubes were subjected to ice impact at energies much higher than would be expected during a launch. None of the ice impact tests resulted in damage to the nozzle cooling tubes. The testing also shows that the nozzle can withstand impacts from rust at sizes greater than allowed on the launch facilities at KSC. The damage limit testing with Inconel wedges proved to be a successful validation of previous analysis work. The shuttle program continues to look for other debris sources. If other sources are determined to be a threat to the SSME, further impact testing may be required.

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